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Cyclone:
A Laser Scanner For Mobile Robot Navigation

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CMU-RI-TR-91-18

The Robotics Institute
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September 1991

91-18139

91 1216 092

REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE September 1991	3. REPORT TYPE AND DATES COVERED technical

4. TITLE AND SUBTITLE
Cyclone: A Laser Scanner for Mobile Robot Navigation

5. FUNDING NUMBERS

6. AUTHOR(S)
Sanjiv Singh and Jay West

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

The Robotics Institute
Carnegie Mellon University
Pittsburgh, PA 15213

8. PERFORMING ORGANIZATION REPORT NUMBER

CMU-RI-TR-91-18

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release;
Distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Researchers at Carnegie Mellon's Field Robotics Center have designed and implemented a scanning laser rangefinder. The device uses a commercially available time-of-flight ranging instrument that is capable of making up to 7200 measurements per second. The laser beam is reflected by a rotating mirror, producing up to a 360 degree view. Mounted on a robot vehicle, the scanner can be used to detect obstacles in the vehicle's path or to locate the robot on a map. This report discusses the motivation, design, and some applications of the scanner.

14. SUBJECT TERMS			15. NUMBER OF PAGES 20 pp
			16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT unlimited	18. SECURITY CLASSIFICATION OF THIS PAGE unlimited	19. SECURITY CLASSIFICATION OF ABSTRACT unlimited	20. LIMITATION OF ABSTRACT unlimited

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Abstract

Researchers at Carnegie Mellon's Field Robotics Center have designed and implemented a scanning laser rangefinder. The device uses a commercially available time-of-flight ranging instrument that is capable of making up to 7200 measurements per second. The laser beam is reflected by a rotating mirror, producing up to a 360 degree view. Mounted on a robot vehicle, the scanner can be used to detect obstacles in the vehicle's path or to locate the robot on a map. This report discusses the motivation, design, and some applications of the scanner.

1. Introduction

Range information is essential for robot vehicle navigation. Even if a robot's path has been preplanned, in a realistic scenario, the robot must perceive obstructions that might interfere with its travel. We have designed and implemented a scanning rangefinder, *Cyclone*, that enables a robot vehicle to determine the three dimensional shape of its environment with high accuracy. The device, built over a period of 18 months starting in mid-1987, has since been used in various configurations for obstacle detection, collision avoidance and more recently for position estimation. Obstacle detection is concerned with locating obstacles in a vehicle's future path so that the vehicle can decelerate from a high speed to a stop before it collides with the obstacle[1]. Collision avoidance involves navigating the vehicle around the detected obstacles to converge with the prespecified path[2]. Although the device was originally designed for the afore mentioned applications, more recently it has been successfully used for position estimation, which is the determination of vehicle location on a map using onboard sensors[3].

At the heart of Cyclone is a time-of-flight ranging device that can make range measurements at up to 7200 hz. In conjunction with a rotating mirror arranged in a periscope like configuration, the system is able to produce radial range scans. The scanner is shown in Figure 1.

Figure 1: Cyclone

In this report we discuss the motivation for such a device, its design and some of its applications. In section 2, we discuss relevant background work and resulting specifications for the scanner. In section 3 we discuss the design of the scanner. Section 4 briefly discusses the applications for which the Cyclone has been used so far. Section 5 discusses some of the salient development issues.

2. Background & Specification

Having chosen ranging as the means to accomplish obstacle detection and collision avoidance, it remained to choose from the many methods possible to obtain range information. In this section we discuss some of these methods and outline the resulting specifications for the scanner.

Several surveys of ranging methods exist in the literature [4,5] and we will only briefly review some of the common methods of obtaining range. Range sensing methods can be classified as either *passive* or *active*. Passive methods derive range information by using ambient energy, typically by analyzing video images of a scene. A commonly used method is called "computational stereo". Either images from multiple cameras at fixed locations (binocular/trinocular stereo) or image sequences from a moving camera (motion stereo) are used. Given a precise difference between camera locations and a means of establishing correspondence between features in the various images, it is possible to obtain range estimates from simple geometric relationships[6,7]. Since computational stereo methods rely on finding a correspondence between features in separate images, the computational effort for such methods depends on the scenes being imaged; in the worst case, a single range image may take minutes to compute. It may not be possible to obtain any range information if the scene has sparse features and hence impossible to obtain a unique correspondence between features in the various images. Other passive methods have been proposed, for example depth from focusing[8] and from analysis of shading[9] of a video image. In general passive methods are vulnerable to poor illumination conditions and have worked best in structured laboratory type settings.

In contrast, active methods project energy onto the scene and are not constrained by ambient lighting conditions. Active methods are further of several types. The simplest type uses triangulation of a projected light beam, much the way that computational stereo does. The correspondence problem is avoided because the projection of the beam can be easily found in the image. The distortion produced by the effect of uneven terrain on structured light can be used to produce three dimensional maps. The feasibility of several devices [10, 11,12] using such a principle has been demonstrated over a range of 1-2 m.

A second method transmits laser energy into the scene and measures the phase shift of the returning signal as compared to that of the outgoing signal. The phase shift can be related to distance within the ambiguity interval of one wavelength. That is, such a sensor cannot distinguish between distance ε and $l + \varepsilon$, where l is the interval of ambiguity corresponding to the distance at which the returned signal is exactly in phase with the outgoing wave. Several devices have been built using this method, and to date this remains the most commonly used method of laser ranging [13].

A third method measures time of flight that pulses of energy take to travel from the sensor to the scene and back. Time-of-flight devices that use ultrasonic, millimeter radar, and laser wavelength waves have been built. Ultrasonic ranging devices can provide reasonable range estimates at small distances (approximately 10-30 cm) and coarse estimates at distances of 2-5 m. The problem with sonar ranging is that most natural objects appear

specular to ultrasonic energy and it is possible to get inter-reflections from corners very easily. That is, most surfaces reflect ultrasonic waves such that the angle of reflection (with respect to the surface normal) is equal to the angle of incidence. Very little energy is returned in the direction of the incident beam and quite often the returned signal measured is reflected off a second or a third surface before it arrives at the sensor. Further, ultrasonic waves are hard to calibrate, since the speed of sound changes with factors such as humidity and temperature, and finally, ultrasonic waves have neither the range nor the speed required for obstacle detection on a fast vehicle.

For shorter wavelengths (as in mm radar and laser), the microstructure of most materials allows the reflection of some energy back in the direction of the incident beam and thus these methods have been more successful. Accurate ranging has been demonstrated by extremely expensive millimeter wave radar devices built for military applications. Though several prototype time-of-flight laser ranging devices have been built [14, 15], until recently, commercially available laser ranging devices have been limited to measuring phase shift. Time-of-flight devices are considerably harder to build because of the timing resolution required: it is necessary to clock pulses on the order of nanoseconds.

Recently, some devices have become commercially available that allow the measurement of the time of flight of laser pulses. These devices, designed for surveying applications, have been demonstrated to measure distances up to 5 km using retro-reflectors. For natural scenes, the range is much shorter, between 50 and 100m. There is a trade-off between the maximum range possible and the dynamic range (the difference between the maximum and the minimum range that can be measured). If it is necessary to make measurements over a large interval, the maximum range must be compromised.

Our primary application, obstacle detection, dictated the functional specifications for the sensor, the scanning mechanism and the electronics:

- Range measurements up to 40 m (maximum) and 3 m (minimum)
- Maximum scan rate between 10-15 hz
- Narrow vertical field of view (between 1-3 lines of range data)
- Angular resolution of less than 1 degree
- Robust enough to withstand extended use (4-6 hours at a time) in natural environments
- Immune to high frequency vibrations from vehicle
- Immune to electromagnetic noise in the environment
- Able to relay data in real time
- Flexible enough so that scanning speeds and angular resolution can be changed easily.
- Cost not to exceed $30,000

The most constraining requirement for ranging is the need to operate in outdoor environ-

mentr where the lighting cannot be controlled. This eliminates the choice of sensors that use passive methods since they are vulnerable to poor lighting conditions. The requirement for speed and accuracy eliminate the choice of sonar and the expense criteria eliminates the choice of radar. Laser ranging through the use of phase shift methods is a reliable technology, but the sensors available at the time of design were limited to a range of approximately 20 m. Recently, some relatively inexpensive laser time-of-flight sensors have been used for surveying applications. The dynamic range specifications and cost limitations led us to choose such an instrument. Further, it is a field tested device that has endured a variety of operating conditions.

The other main decision was that of scanner configuration, the mechanical system in which the laser is housed and which determines the distribution of the laser beam emanating from the range finder. Since the objective is to recognize obstacles on an otherwise flat road, we didn't think it necessary to use a dual axis range scanner (with a nodding as well as rotating mirror) that typically provides from 80 to 256 lines of range data per frame. Most of these devices are slow, providing 2 frames per second at the most. Rather, what we wanted was less data, but more often. It was estimated that 10 scan lines/second from a single line scanner would be necessary for obstacle detection at speeds of 10 m/s.

3. Scanner Design

3.1. Configuration

We considered two configurations for the scanner to distribute a laser beam from a single point source. The first one involved rotation of the entire rangefinding device. The advantage of such a configuration is that laser energy transmitted and received is not attenuated by mirrors or prisms. However there are several complications. It is necessary to use a large sophisticated slip-ring to transfer data and power to the instrument. Further, spinning a mass of several pounds brings risks stability, and increases vulnerability to natural elements and accidents.

The second configuration we considered used a rotating mirror to point the beam. This involved rotation of a tube containing a mirror (with an adjustable set angle) above the rangefinder aperture. The advantage of such a method is that the rangefinder itself is not required to move, making a safer and simpler mechanism. This design was chosen and implemented. Designed to be mounted on the front of an autonomous vehicle, the system consists of several parts:

- Scanner enclosure: houses the rangefinding unit, a DC motor/encoder, rotating tower and an interface circuit

- Power and communications enclosure (PCE): provides the power and control signals for the scanner motor. It also contains circuitry to buffer range data from the rangefinder and to relay these data to a host computer.

- Host computer: connected to the PCE by a parallel data interface to read buffered range data. Apart from processing the range data, it is also responsible for sending high level control commands (motor speed, etc.) to the PCE. These are then turned into low level controls sent to the motor.
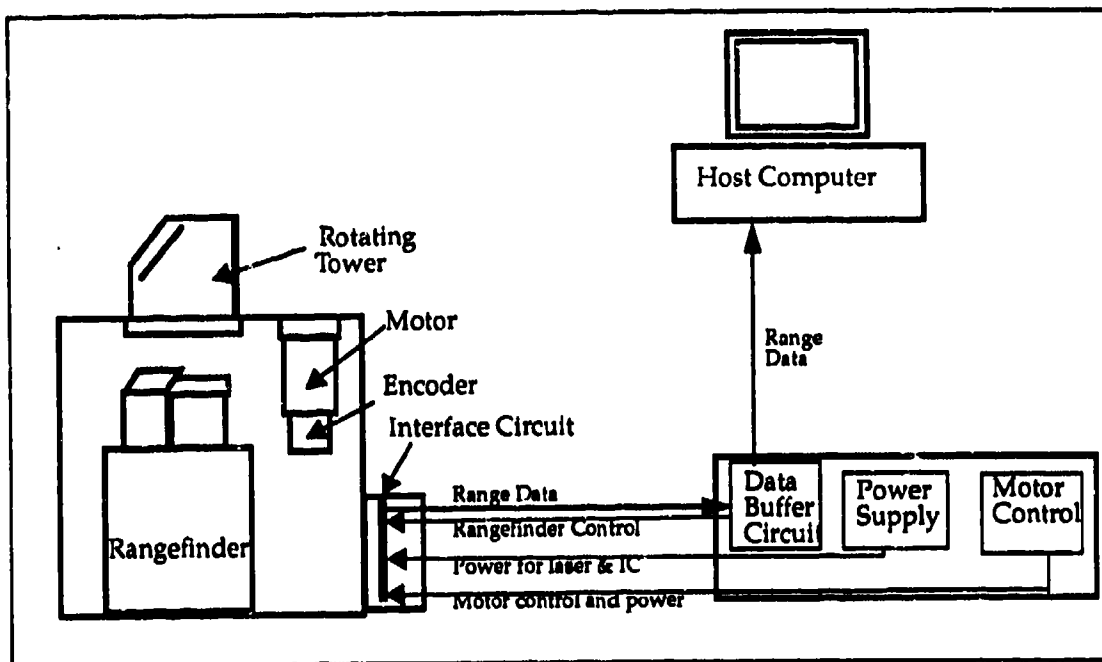
These modules are shown in Figure 2.

Figure 2: Configuration of the system

3.2. The Rangefinder

Cyclone uses a customized version of a commercially available single point laser ranging device (RF-90) [1]. Salient features of the sensor are:

Wavelength	0.9 micrometer
Laser	Gallium Arsenide Semiconductor
Pulse repetition rate	7200 Hz
Range	3 - 50 m
Accuracy	+/- 15 cm
Beam spread	2.5 mrad
Resolution	10 cm
Power requirements	12 V DC, 1A.

The instrument is able to time the flight of laser pulses transmitted and returned from naturally diffuse objects. Figure 3 shows the configuration of the hand-held sensor as it is commercially marketed. The device has been modified such that rather than being trig-

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1. Built by RadarTechnik and Elektrooptik, Austria.

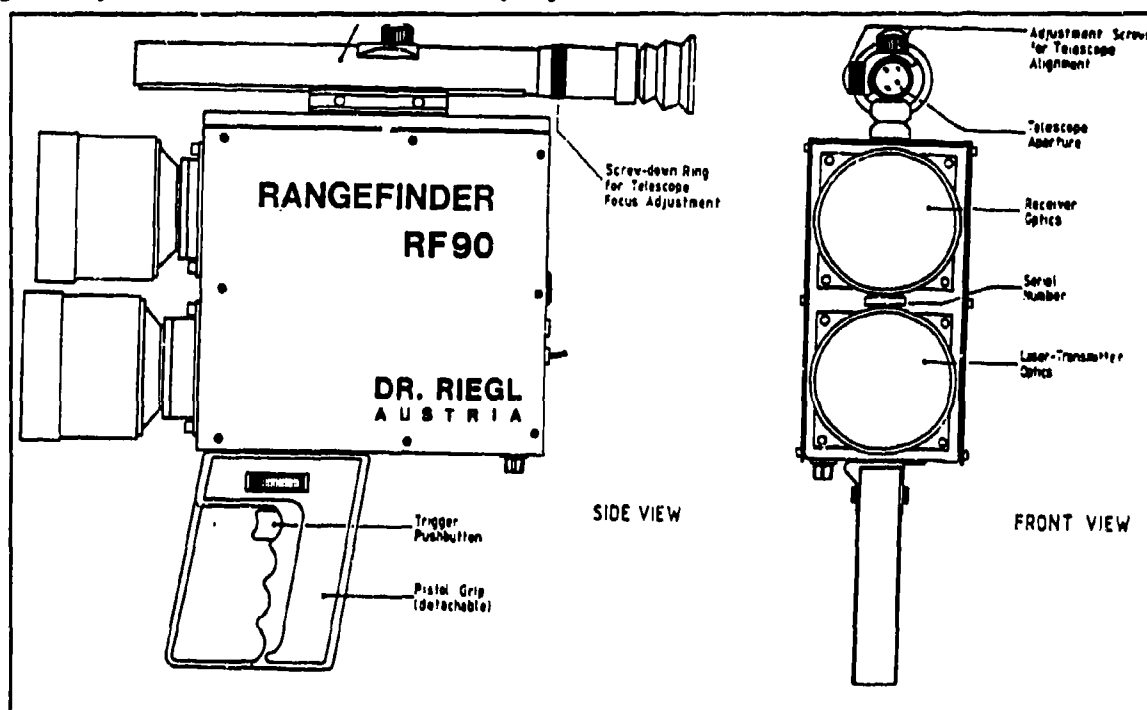gered by hand, the laser is activated by a pulse train.

Figure 3: The rangefinder

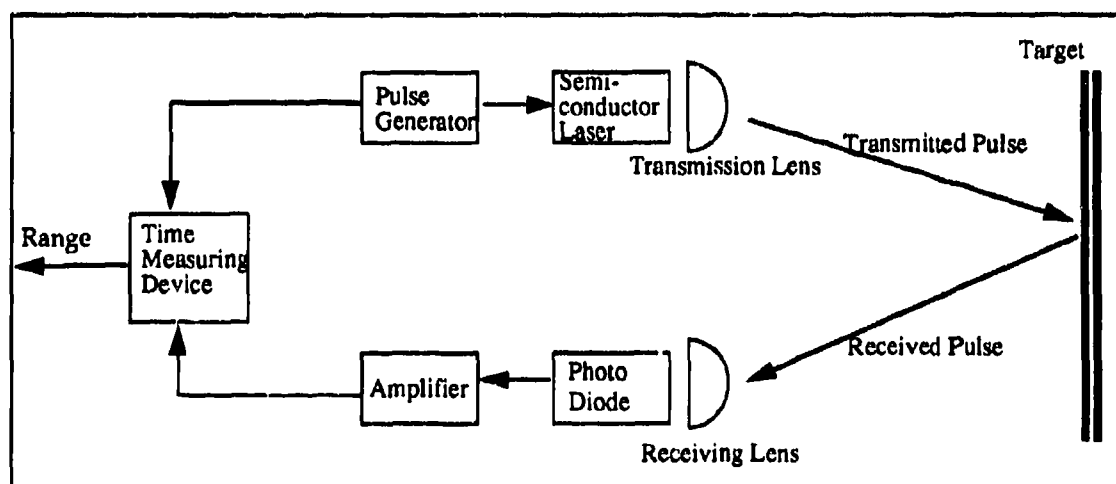Figure 4 shows a block diagram of the operation of the rangefinder.

Figure 4: Operation of rangefinding device

Other researchers have done additional work on calibrating the sensor and have found that it is possible to reduce range error, especially for measurements taken from distances of less 3 m [16, 17].

3.2.1. Interfacing with the RangeFinder

When the rangefinder is triggered, the measured range is output on an 11 bit parallel port. Specifically, two control lines must be manipulated for the rangefinder to take a measurement:

- TRIGGER is a control line that, when given a rising edge, causes the rangefinder to produce a range measurement.

- LASER_INHIBIT is a control line that must be driven low for the TRIGGER inputs to be effective. We have used this line for safety purposes by ensuring that this line is never pulled low unless the tower is rotating.

Additionally, two status lines are available:

- DATA_VALID is a status line. It is held high only when a good echo (reflected signal) is received by the rangefinder.

- DATA_READY is a status line which is held high when the data are ready to be read. This line is always high except for 20 microseconds while the data are in transition.

Reading data from rangefinder can be accomplished by the following algorithm. A count down timer is started after a TRIGGER pulse is issued. Immediately, a loop is initiated that checks to see if the DATA_VALID line has been pulled high. If this doesn't happen by the time the timer completes, the data are considered to be "missing". If the DATA_VALID line has been pulled high, then the algorithm waits for the DATA_READY line to be pulled high. As soon as this is done, the parallel port can be read.

3.3. Scanner Enclosure

The scanner enclosure houses the rangefinder as well as the necessary optics and electronics. Figure 5 shows a cut away view of the scanner. The noteworthy components are as follows:

- Rotating Tower: A rotating tower at the top of the scanner enclosure, contains a mirror that reflects the transmitted and receiving beams. The tower is driven by a cog belt powered by a motor. There is a 2:1 gearing ratio between the motor and the tower. A four point bearing is used to hold the tower rigidly.

- Motor/Encoder: A DC stepper motor is used to drive the rotating tower. The encoder allows for the motion control to determine position of the motor shaft to within 0.2 degrees.

- Interface Circuit: This circuit is responsible for relaying power and data between the scanner and the remote PCE.

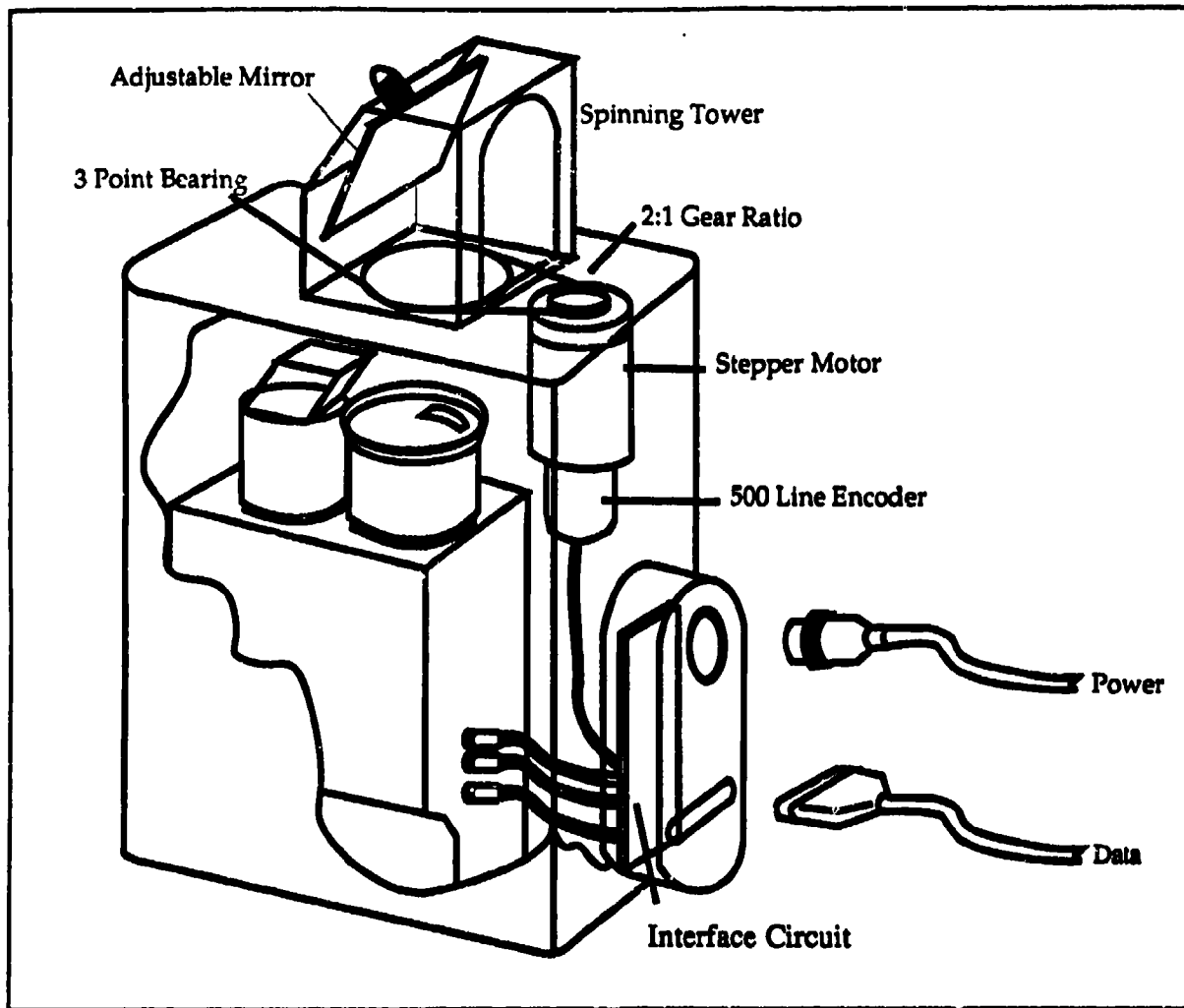Figure 5: Scanner enclosure

• Tower Motion Sensors: These sensors, mounted directly below the tower, have two functions. Firstly, they ensure that if the speed of the tower falls below a minimum speed, the laser is disabled from firing, so as to not repeatedly fire the laser at one spot. This is a safety feature designed to minimize exposure to eyes, in case the tower stalls for some reason. A second sensor is used to mark an angle (between the two sensors) in which the laser can be selectively disabled. Typically, the laser scanner is mounted on the front of a vehicle, and the field of interest is in the 180 degree area in front of the vehicle. The vehicle itself will block the rear portion of the 360 degree scan area. The second tower motion sensor enables the determination of whether the tower is pointing out in front of the vehicle or towards it. This information can be used to disable the rangefinder from firing when the tower is pointing towards the vehicle. The second motion sensor is mounted 170 degrees away from the first one. This is used to indicate a "deadband" on part of the 360degree view(Figure 6).
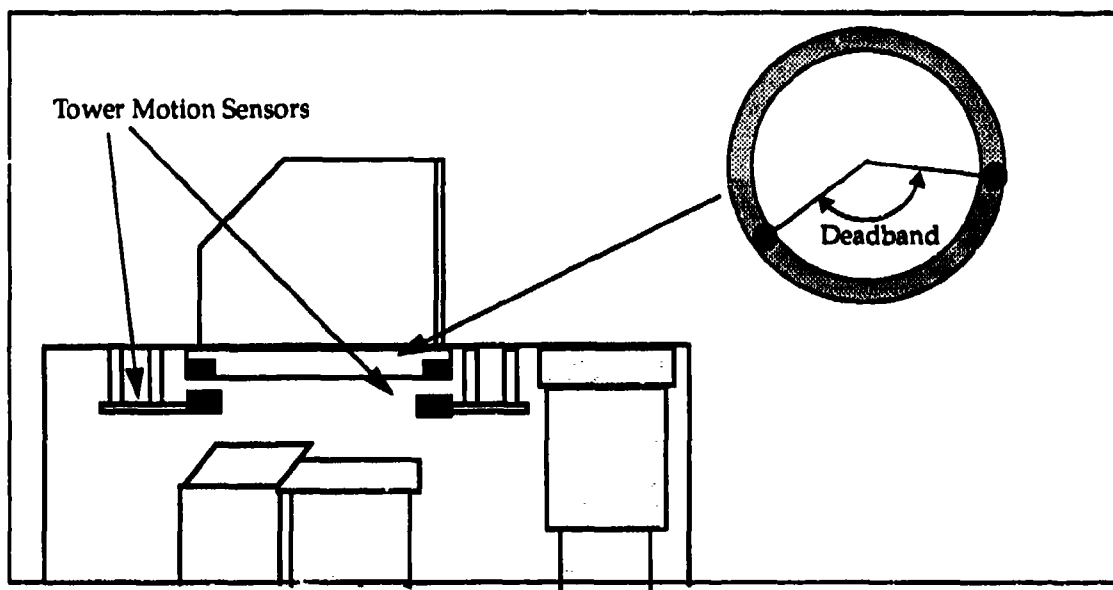
9

Figure 6: Tower motion sensors

3.4. Power and Communication Enclosure

As mentioned previously, the power and control signals are not generated in the scanner enclosure. Instead a separate enclosure has been designed (PCE). When the cyclone is mounted on the front of an autonomous vehicle, the PCE is rack mounted in the interior in a 19" rack. The PCE houses the following:

- Data Buffer Circuit: generates the control signals for the rangefinder, and buffers the range data till a complete scan can be transmitted to the host computer.

- Motor Amplifier: generates the power and control for the motor that drives the tower.

- Power Supply: Converts the AC voltage to DC for use by the buffer circuit (12 V @0.25 A, 5V @3A) and to power the rangefinder (12 V@ 1A) and the interface circuit (5V @ 0.1 A).
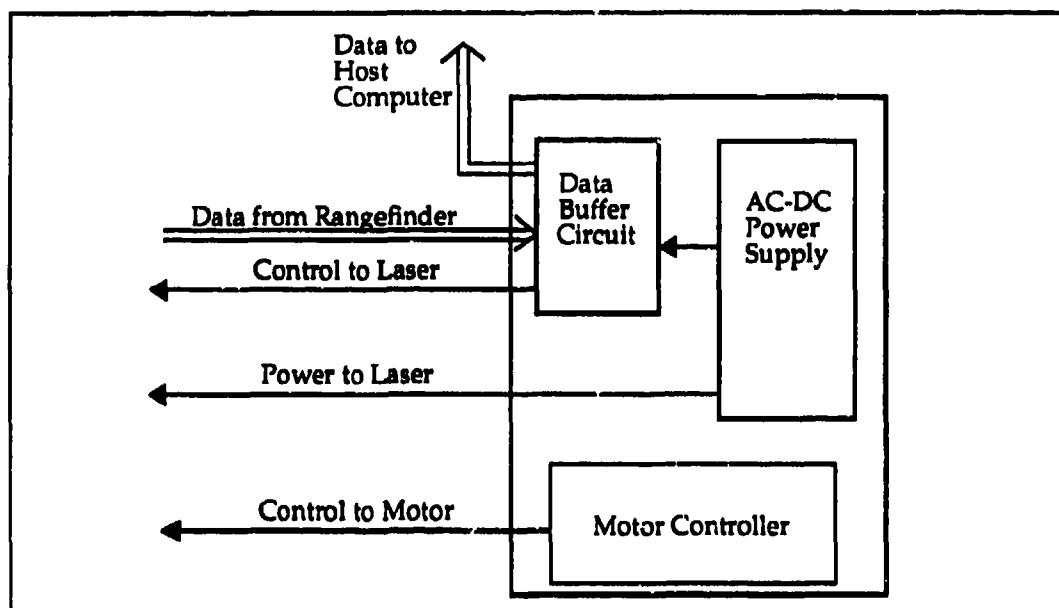
The configuration of the PCE is shown in Figure 7.

Figure 7: Power and Communication Enclosure

3.5. Motion Control

It is necessary to precisely control the speed of the scanner tower and hence the speed of the DC motor used to drive the tower. We were looking for a motion control system that afforded us the following:

- Precision of control: max 0.1% error in rotational velocity

- Simplicity: a simple stand-alone system that can communicate over a serial interface for high level commands and diagnostics.

- ability to synchronize: each data set should be distinct, i.e, it is necessary for the motor to be repeatedly synchronized with the zero angle.

We chose a high resolution DC stepped motor[1] that is controlled by a single stand-alone unit providing all the necessary control and power to drive the motor. This device has 25000 steps/rotation and is comparable in smoothness to the DC servo motor. This motor provides 45 in/oz. of torque. Its top speed is 1800 RPM corresponding to 15 rotations/sec of the tower. Specifications of commands like motor speed and motor diagnostics are achieved through a serial interface on the motor controller.

An encoder is mounted on the shaft of the motor and provides three separate lines from which the position of the motor shaft can be precisely determined. Channels "A" and "B" produce a pulse train of 500 pulse/rotation that is 90 degrees out of phase. This provides 2000 edges (1000 rising and 1000 falling) from which the angular position of the motor can

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1. Manufactured by Compumotor Inc.

be determined. The "Z" channel produces a pulse whenever the motor completes one complete rotation.

3.6. Electronic Design

There are two main circuits: the *Interface Circuit* that resides in the scanner enclosure, and the *Data Buffer Circuit*, that resides in the PCE. The interface circuit transmits range data as it is obtained to the data buffer circuit via differential drivers and receivers. Range data are collected by the Data Buffer Circuit until the tower makes one full revolution. These data comprise one scan. When a scan is complete, the buffer circuit signals the host computer, whereupon the entire scan is transferred to the host computer for processing.

3.6.1. Interface Circuit

The Interface Circuit has three functions. First, it acts as a safety monitor. It uses one of the tower motion sensors to sense if the tower has stopped rotating. In this case, the LASER_INHIBIT signal is pulled high and the rangefinder is disabled from firing. The second function is to disable the laser from firing for part of the 360 degree scan area as mentioned earlier. This feature extends the life of the laser diode and also makes it possible to rotate the tower at a faster rate because the 7200 Hz firing rate is a RMS specification. However, for applications where a 360 degree scan is needed, the disable feature can be turned off.

The third function of the circuit is to convert signals between single ended and differential form. TTL signals (range measurements) from the rangefinder are differentially transmitted to the buffer circuitry, and differentially transmitted signals from the buffer circuitry are converted to TTL levels. That is, each signal is transmitted on two separate lines, such each signal is now the difference between the voltage on two lines. Ambient noise affects both lines equally, but difference between the two lines is preserved. This procedure prevents noise contamination along the cable connecting the scanner and the PCE.

3.6.2. Data Buffer Circuit

The Data Buffer Circuit has three functions: to synchronize firing of the laser with the angular position of the tower, to buffer range data from one complete scan, and to transmit the scan to a host computer. Scan data are collected and stored in two memory banks. This avoids shared memory and synchronization problems between scan storage and scan transmission. Data for a new scan is stored in one bank while the previous scan is being transmitted from the other bank. This allows for more effective utilization of the CPU on the host computer since the host computer receives a whole scan at a time, rather than having to fetch one range measurement at a time.

Synchronization of the scans, i.e. correct detection of the start of a new scan is accomplished by the use of two quadrature pulse trains issued by the encoder: the Z and A channels. The Z channel is asserted once per motor shaft revolution. The A channel pulses

1000 times per revolution of the motor shaft. One additional signal is needed to fully synchronize the scan field with the encoder signals. Since there is a 2:1 gearing ratio between the motor and the tower, two pulses are received on the Z channel and 2000 pulses are received on the A channel per rotation of the tower. It is therefore not possible to differentiate between the beginning of the first half of the scan and the beginning of the second half. To fully synchronize the scan field, the DB (dead band) signal generated by the interface circuit is used. The DB signal, used to disable the laser from firing in the back half of the scan, allows the differentiation of the front and back halves of the scan. The Z and DB signals together indicate the beginning of the scan.

The second task, buffering data for one complete scan, is accomplished through the A channel. The 2000 pulses of the channel are divided by either 2, 4, 8, or 16 (selected through DIP switches on the circuit board). This allows the number of data points per scan to be varied between 1000, 500, 250, and 125. The divided signal is used to trigger the laser rangefinder at appropriate angular intervals, and to store the resulting range data in memory.

The sequence of events is as follows. W (write) is asserted one clock cycle after a rising edge on the divided A signal. At this point, data from a previous T (laser trigger) is available and is stored in memory. T is asserted the following clock cycle, triggering the laser and putting the resulting range data onto the memory input bus. This data are written on the next W pulse, repeating the cycle. The timing relationships are depicted in Figure 8:
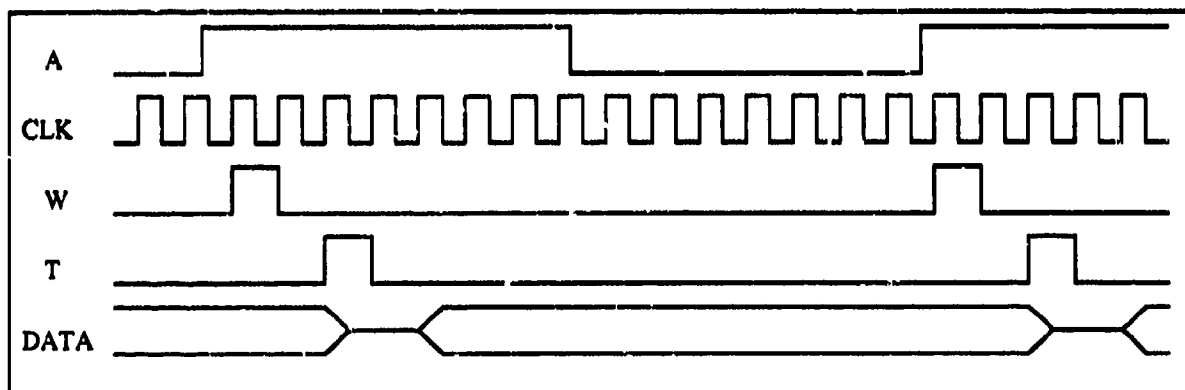

Figure 8: Communication between the Interface Circuit and Data Buffer Circuit

The final task of the buffer circuit is to transmit the scan data to a computer for processing. Completed scans are signaled by the Z and DB signals (the beginning of a scan is also the end of a previous one). Upon sensing a completed scan, an interrupt request line is asserted and remains so asserted until either the mirror has made half a revolution or the computer acknowledges the interrupt. In the first case, the half revolution of the mirror is signaled by a subsequent Z pulse and indicates a time out condition; the computer has failed to respond and the data are lost. Normally, the interrupt is acknowledged by the host computer and upon its receipt, STR (data strobe) is asserted and held until IBF (input buffer full) is received. During this time, data are put on the data bus and may be read by the computer. Data is valid on the bus until IBF is asserted,

at which time STR is deasserted and the data removed from the bus. Once the computer detects the de-assertion of STR, it deasserts IBF. This causes STR to be asserted for the next piece of data, repeating the cycle. The simplified timing diagram is shown in Figure 9.
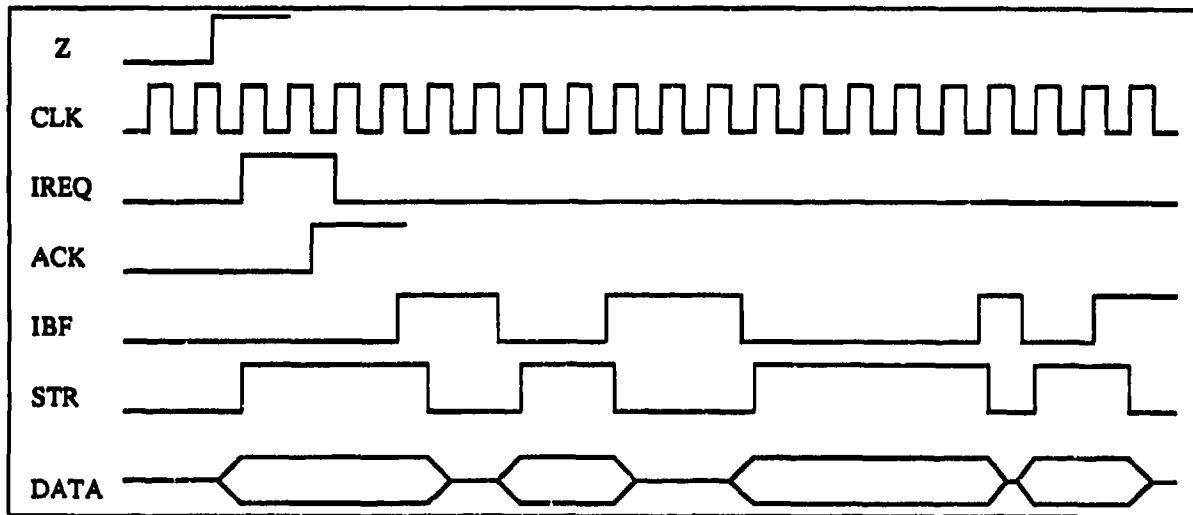

Figure 9: Communication with the host computer

4. Applications

4.1. Obstacle Detection

In our early obstacle detection and avoidance experiments, we mounted Cyclone on the front bumper of the Navlab. In this configuration, the scans lie in a plane parallel to the ground plane and only obstacles higher than this plane can be detected. This configuration is shown in Figure 10.
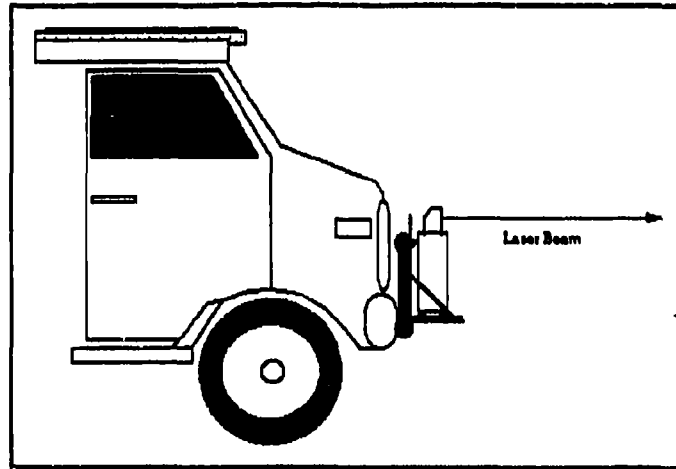

Figure 10: Cyclone mounted on the front bumper of NavLab

The scanner is mounted on a "L" bracket using five shock mounts to damp out high frequency vibration which are mainly induced by the vehicle engine.

Cyclone was also used in a downward looking configuration to obtain three dimensional information about the terrain. In Figure 11, the scanner is shown mounted in a "pendulum" configuration atop of the cab of the NavLab. The scanner pivots around a horizontal axis to the ground plane and runs through the left and right sides of the scanner. The downward pointing angle can be adjusted by a link at the bottom of the
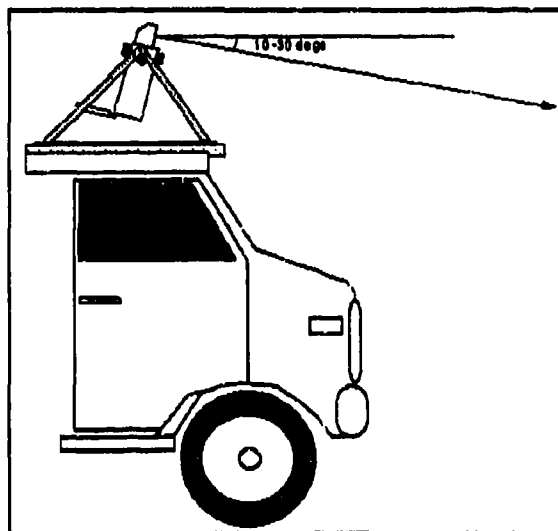
scanner.

Figure 11: The "pendulum" mount for 3-D scanning

4.2. Use on the LE (360 radial scan)

More recently, Cyclone has been used for position estimation on the Locomotion Emulator (LE), one of the robots developed at the Field Robotics Center. Given the angular resolution and range accuracy of the scanner, it is possible to match features in the range data to known features on a map such that the position of the robot can be located to within 10 cm. Figure 12 shows the Cyclone mounted on the LE.
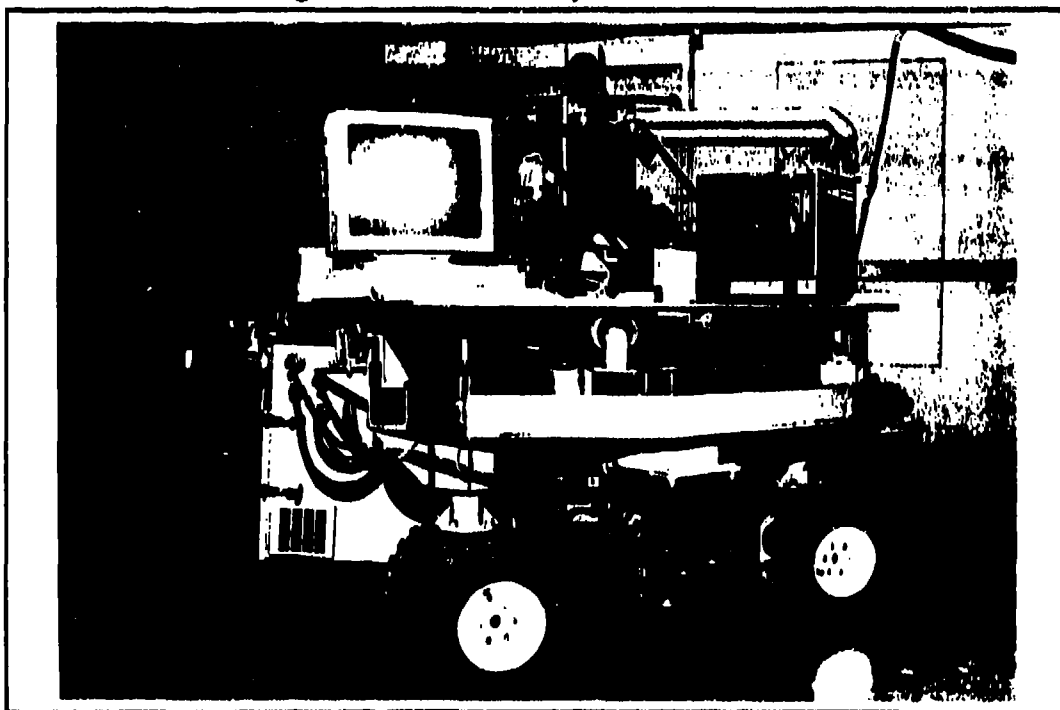

Figure 12: Cyclone mounted on the Locomotion Emulator

Figure 13 shows data from a single scan taken from the Cyclone while the LE was navigating in an underground mine intersection. This scan consists of 1000 range measurements.
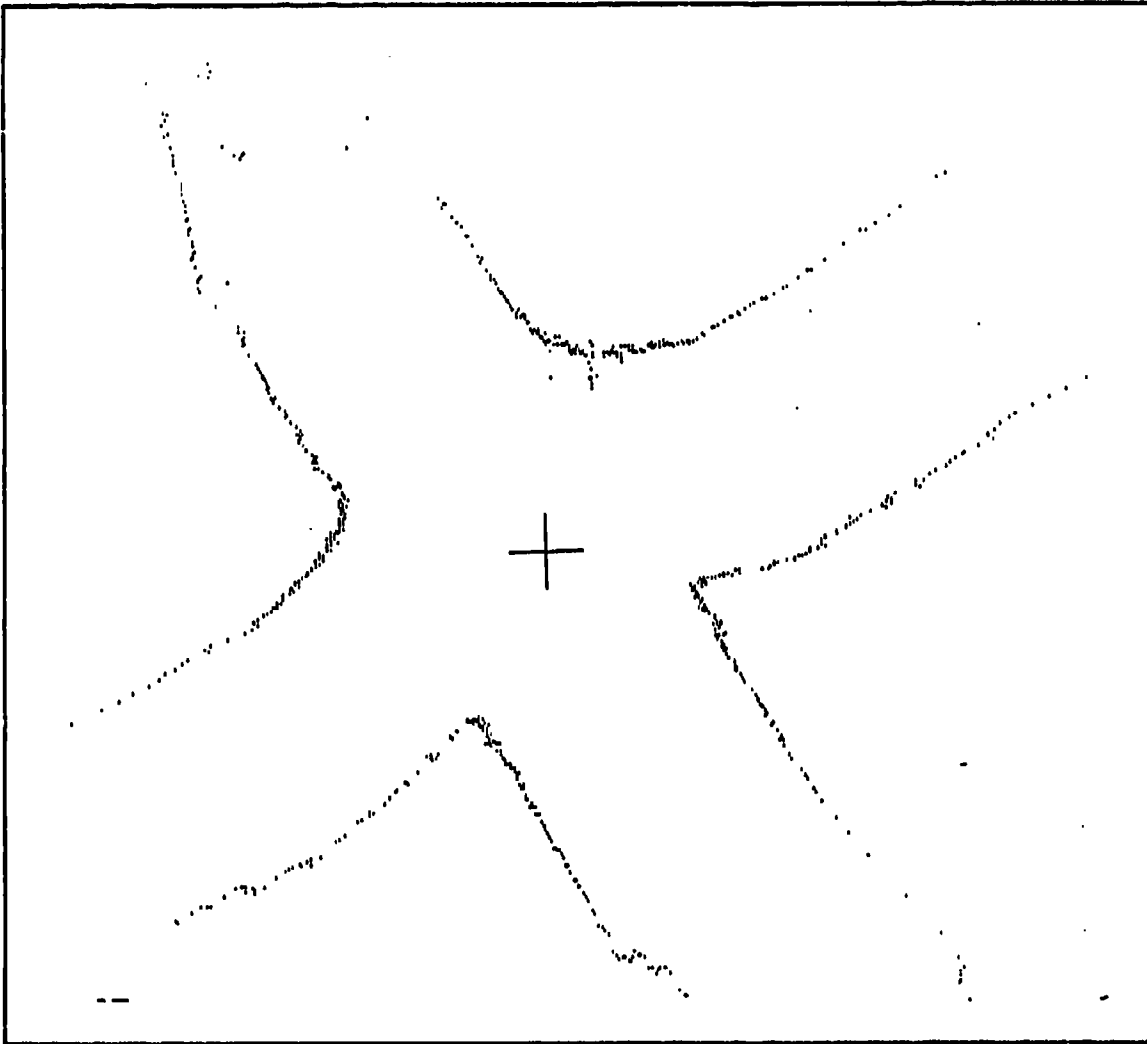

Figure 13: Sample data obtained from the Cyclone

5. Discussion

Development of a stable system was complicated by several factors. Firstly, we were plagued by electrical noise problems. The stepper motor used to drive the scanner tower was the largest source of noise. Even after much shielding, data communication was constantly contaminated. This problem was solved by differential transmitting all signals between the scanner enclosure and the PCE.

We had a hard time finding a glass dust cover for the front of the tower. We found that quite often laser pulses were reflected back from the glass cover and were accepted as legal echoes. This was despite many efforts to treat the window with special coatings matched to the frequency of the laser, and to tilt the window. This problem has never been solved and it was determined that a modification in the rangefinder itself is necessary to compensate for this phenomena. For our experiments, we ended up manually removing a metal dust cover as necessary. Under most operating conditions (i.e. in the absence of a lot of dust), motion of the tower is sufficient to keep dust from entering the scanner.

A different set of problems are application dependant. For example, at high speeds, the lines traced by a scan on the ground (while mounted in the downward looking configuration) are not orthogonal to vehicle motion but lie at a velocity dependant angle to it. This is due to the relatively large amount of time taken by the rotation of the tower; the tower speed must be increased proportional to the higher vehicle speeds to prevent this effect. Another problem is due to the pitching motion of the vehicle that the Cyclone is mounted on. Given the small vertical field of view, the scan could completely miss the road (and hence any obstacle) or give the erroneous impression that the road surface lies much closer than expected. It is necessary to actively servo the pitch axis of the scanner to maintain a desired downward looking angle. This issue was also never dealt with.

Cyclone has proven to be a much larger success for applications other than the ones it was designed. Recent results in map based position estimation when mounted on a slow moving vehicle, navigating in underground mines, are unprecedented. The range and the accuracy afforded by the system make it ideally suited for this sort of application.

Acknowledgments

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